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Molecular Tagging Velocimetry (MTV) was used to study vorticity dynamics in several flows under investigation for mixing enhancement and control. The evolution of streamwise vorticity, responsible for a large increase in mixing in a confined wake flow, was measured. It was found that the streamwise vorticity has a peak value in excess of 70% of the peak spanwise vorticity. The MTV technique was extended to allow simultaneous whole-field measurements of the velocity and a passive scalar on the basis of molecular tagging diagnostics. This new approach also offers a new capability for simultaneous flow visualization and vorticity mapping. The application of MTV to the study of unsteady separation resulted in boundary-layer resolved measurements of flow separation in the vortex-ring/wall interaction and dynamic stall over a pitching airfoil. The measurements of flow separation over a pitching airfoil, believed to be the first boundary-layer resolved measurement of this phenomenon, show that the process of boundary layer separation occurs over a shorter time scale, and is more eruptive, than that captured by the computations to date.

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Application of Molecular Tagging Diagnostics to Turbulent Mixing Enhancement and Control Studies

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Executive Summary

The technique of Molecular Tagging Velocimetry (MTV) was used to study vorticity dynamics in several flows under investigation for mixing enhancement and control. The evolution of streamwise vorticity, responsible for a large increase in mixing in a confined wake flow, was measured. The MTV technique was extended to allow the simultaneous whole-field measurement of the velocity and a passive scalar (concentration, in this case) on the basis of molecular tagging diagnostics. This new approach also offers a new capability for simultaneous flow visualization and vorticity mapping. The application of MTV to the study of unsteady separation resulted in boundary layer resolved measurements of flow separation in the vortex-ring/wall interaction and dynamic stall over a pitching airfoil. The measurements of flow separation over a pitching airfoil, believed to be the first boundary-layer resolved measurement of this phenomenon, highlighted the need for refinement in the computational methods used to date for analyzing this problem.

Over the last three years, this AASERT program provided either full or partial support for the education and training of 3 graduate and 2 undergraduate students. During this period, two journal articles, two conference papers, and one PhD thesis were published. These are detailed below.

Associated Personnel

Charles Gendrich	Ph.D. Candidate (Jointly supported by NSF)
Richard Cohn	Ph.D. Candidate (Jointly supported by NSF and the Palace Knight Program)
Douglas Bohl	Ph.D. Candidate (Jointly supported by NSF)
Colin MacKinnon	Ph.D. Candidate (Supported by NSF)
Scott Krueger	Undergraduate (Jointly supported by NSF)
Stephanie Bonin	Undergraduate

Publications

1. Gendrich, C. P. and Koochesfahani, M. M. [1996] "A spatial correlation technique for estimating velocity fields using Molecular Tagging Velocimetry (MTV)," *Exp. Fluids*, **22(1)**, 67.

2. Koochesfahani, M. M., Cohn, R. K., Gendrich, C. P., and Nocera, D. G. [1996] "Molecular tagging diagnostics for the study of kinematics and mixing in liquid-phase flows," Proceedings of the Eighth International Symposium on Applications of Laser Techniques to Fluid Mechanics, Lisbon, Portugal, July 8-11, 1996, 1.2.1.

3. Gendrich, C. P., Koochesfahani, M. M., and Nocera, D. G. [1997] "Molecular Tagging

Velocimetry and other novel applications of a new phosphorescent supramolecule," *Exp. Fluids*, **23(5)**, 361.

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5. Gendrich, C. P. [1998] "Dynamic stall of rapidly pitching airfoils: MTV experiments and Navier-Stokes simulation," PhD thesis, Michigan State University.

1. Introduction

The purpose of this work is to develop molecular tagging techniques for the investigation of flow kinematics and simultaneous velocity/passive scalar measurements. Our initial applications of this capability are to the study of mixing enhancement and control in addition to unsteady separation and vortex dynamics.

Molecular tagging diagnostics take advantage of molecules with long-lived excited states for non-intrusive, multi-point measurements of various fluid dynamical quantities. The technique relies on the capability to tag portions of the flow by a laser and monitor their subsequent evolution over the luminescence lifetime of the molecule.

2. Diagnostics Developments

Our developments to date have centered around a water-soluble triplex phosphorescent compound, alcohol/CD cup/lumophore, developed by Nocera's group in MSU's Chemistry Department [1,2]. In anticipation of applications with non-uniform mixtures (simultaneous concentration/velocity measurements being one example), a two-detector imaging system has been developed for acquiring an image of the initially tagged regions and a subsequent image of these regions convected by the flow over a prescribed time delay Δt later. The Lagrangian displacement vectors from such image pairs are computed using a spatial correlation technique. This generalized approach also offers added benefits in the case of Molecular Tagging Velocimetry (MTV) when using uniform mixtures. For example, it relaxes the requirement that the initial tagging pattern be known *a priori*, and eliminates the errors in velocity estimates caused by variations in the tagging pattern during an experiment.

The direct spatial correlation technique we have implemented for estimating the Lagrangian displacement vector from MTV image pairs provides significant improvements in measurement accuracy compared to existing analysis approaches. Based on both experiments and an extensive statistical study on the performance of this correlation approach, we have found that we can typically measure the displacement of the tagged regions with a 95% confidence limit of ± 0.1 subpixel accuracy. Details of these developments have been published in References [3-5] and will not be repeated in this report. For completion, we mention that our work in this area has also been extended to gas-phase flows by taking advantage of phosphorescent molecules used in Nitrogen flows [6-8]. The following section highlights our work over the past three years in terms of the specific flows we have investigated, and the development of the capability for simultaneous whole-field measurements of velocity and passive scalar.

3. Results

1. *MTV Measurements of Unsteady Separation in Vortex Ring/Wall Interaction*

When a vortex ring approaches a solid surface at normal incidence, the unsteady adverse pressure gradient on the wall results in boundary layer separation and the formation of a secondary ring of opposite sign. We have used this flow as a test bed for our MTV developments, since it is relatively simple to set up but contains many of the essential elements of other flows of interest. These include a highly unsteady vortical flow, vorticity interaction with a surface, thin boundary layers which separate, and vortex-vortex interactions. Data are in the form of time series of the whole-field measurements of the radial and axial velocity components (υ_r and υ_z) over the (r-z) plane. The azimuthal vorticity component ω is then estimated from the velocity data using a second-order finite difference method.

The vorticity field shown in Figure 1 depicts two instants near the onset of boundary layer separation. The origin of time is arbitrarily chosen to correspond to the valve opening in the vortex ring generator. Note that only the flow to the right of the vortex axis is shown. The data have sufficient spatial and temporal resolution to allow the detailed analysis of the boundary layer separation process. For example, the data in Figure 1 clearly show the onset of separation as the boundary layer starts to erupt (t = 1.63s) and its culmination in a recirculation zone near the wall (t = 1.70s). The time evolution of the boundary layer vorticity distribution at the wall, shown in Figure 2, identifies how and when the region of recirculation develops (in this case, positive vorticity near radial location r = 3.2 cm). We believe these data may be the first whole-field experimental results for the ring/wall interaction with this level of resolution to allow comparison with previous boundary-layer computations of Walker, et al. [9], and numerical results of Orlandi & Verzicco [10].

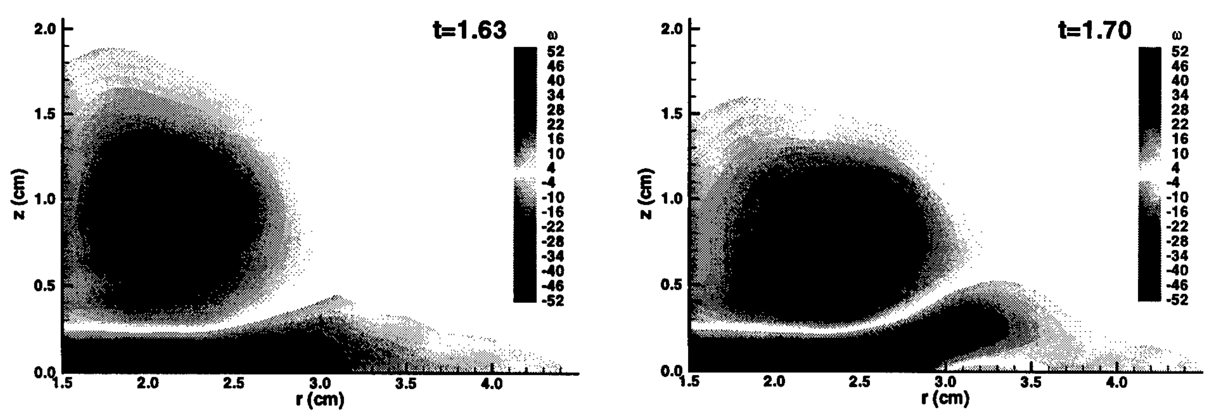


Figure 1. Vorticity field at two instants near the onset of separation.

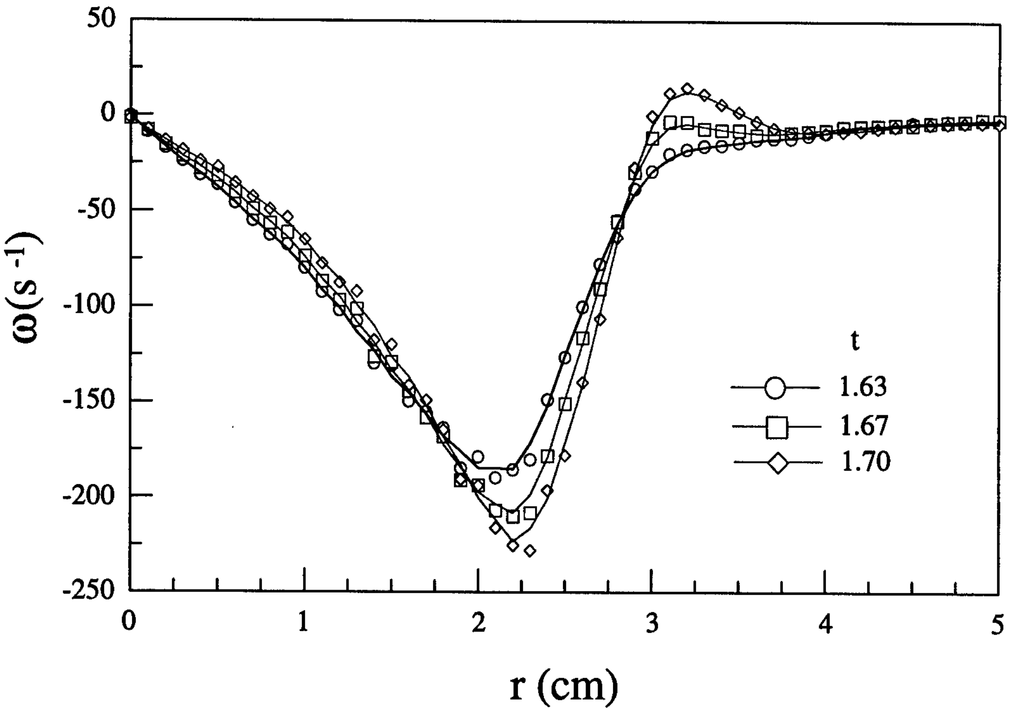


Figure 2. Time evolution of the wall vorticity distribution near the onset of separation.

Some of the results from this investigation have been presented in the 1997 AIAA Conference in Snowmass, Colorado [11]. These results indicate that pairing of the secondary and tertiary vortex rings is not an essential physical mechanism leading to the ejection of the secondary vortex ring from the near-wall region, as was suggested by Orlandi & Verzicco [10]. Further analysis is in progress to compare the non-dimensional time to the onset of boundary layer separation with that predicted by Walker, et al. [9].

2. *Boundary-Layer Resolved Measurements of Unsteady Leading Edge Separation on a Two-Dimensional Pitching Airfoil*

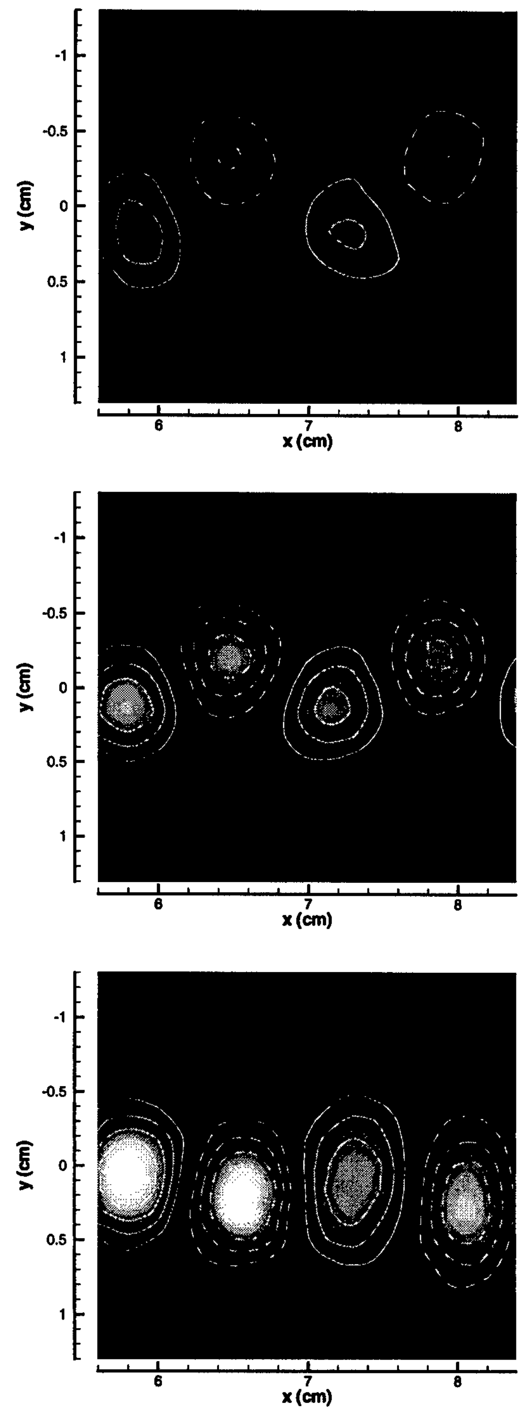
When an airfoil pitches rapidly to high angles of attack, the flow can remain attached well beyond the static stall angle. The flow will eventually separate from the leading edge culminating in the formation of the dynamic stall vortex. While this flow has been the subject of numerous studies, the details of the flow within the boundary layer at the onset of separation have not been captured experimentally to date. As part of a joint experimental/computational effort, we have recently obtained the first boundary-layer resolved measurements of flow separation near the leading edge of a pitching airfoil [12]. The data provide a detailed picture of the evolution of the velocity and spanwise vorticity for an airfoil executing a ramp motion trajectory. Results are being

compared with our 2-D Navier-Stokes computations (in collaboration with Dr. Miguel Visbal of Wright-Patterson Air Force Base) and other higher resolution computations [13] which have been obtained for flow conditions similar to our experiments. The major conclusion from our experimental data is that the process of boundary layer separation occurs over a shorter time scale, and is more eruptive, than that captured by the computations. Further analysis of the experimental data and comparison with computations are in progress. We believe these experimental data will be very useful for refining the computational procedures needed for such highly unsteady flows with spatially localized boundary layer separation. The details of this work are found in the recently completed PhD thesis of Dr. Charles Gendrich [12].

3. *Mixing Enhancement in a Forced Wake*

The purpose of this part of our work is to quantify the vorticity evolution in the flow field of the forced wake of a splitter plate inside a confining geometry. The interest in this flow stems from the fact that forcing a low Reynolds number 2-D wake can lead to a highly three-dimensional flow and a large increase in mixing [14]. Our recent estimates, based on chemically reacting LIF measurements, report the amount of molecularly mixed fluid in terms of mixed-fluid fraction to be 2.5 to 3 times larger than that in high Reynolds number natural two-stream mixing layers [15]. Both reacting and non-reacting LIF data connect this increase in mixing to the downstream evolution of the streamwise vorticity, which is generated by the reorientation and stretching of spanwise vorticity near the side walls of the flow facility. The resulting flow is highly three dimensional, and this application highlights the capability of MTV to make measurements when strong out-of-plane motions are present. It is believed that understanding the vorticity interaction with walls, its dynamics and downstream evolution which lead to such large increases in mixing in this flow will be helpful to an overall strategy for mixing enhancement and control. This work, which is part of the PhD thesis of Mr. Richard Cohn, is to be completed in the first quarter of 1999. Examples of typical data emerging from this study are highlighted below.

The time series of the instantaneous velocity vectors (u, v components) in the streamwise (x-y) plane have been obtained at several spanwise (z) locations. The spanwise vorticity field ω_z is estimated from the measured velocity field by a second-order finite difference scheme. These data allow us to investigate the temporal and downstream evolution of ω_z at different forcing amplitudes. Typical data at mid-span are shown in Figure 3. The vorticity field of the alternating-sign vortex array and its spatial arrangement, previously noted through LIF visualization, is quantified. It can be seen that the lateral spacing of the vortex array reduces and the peak vorticity increases as the forcing amplitude increases. Note also that the decrease in the peak vorticity due to diffusion, as the flow moves from left to right, is captured.



amplitude = 2%

amplitude = 5%

amplitude = 9%

Figure 3. Wake ω_z distribution at midspan for one phase in the forcing cycle for different amplitudes. Vorticity contours are ±5, ±10, ±15, ... (s^{-1}). Dashed lines indicate negative vorticity.

These data have been complemented by measurements of the velocity vectors (v, w components) in the spanwise (y-z) plane and the streamwise vorticity field ω_x. Typical results showing the downstream evolution of ω_x are shown in Figure 4. In this figure, the streamwise flow direction is out of the page and the imaged area corresponds to the right half of the test section cross sectional area. The vorticity field of the alternating-sign streamwise vortex pair near the side wall (z = - 4 cm) at early x locations, previously noted through LIF visualization, is quantified. As the flow proceeds downstream, the spatial arrangement and dynamics of the streamwise vorticity become more complex, the peak value of the vorticity decreases and the region containing the streamwise vorticity moves away form the side wall towards the center (z = 0) of the test section. An important result is that the streamwise vorticity has a peak value in excess of 70% of the peak spanwise vorticity. We are hoping to combine the spanwise and streamwise vorticity data to construct a volumetric picture of the vorticity field. The final goal of this study is to link the dynamics and evolution of the vorticity field to the increased mixing quantified previously.

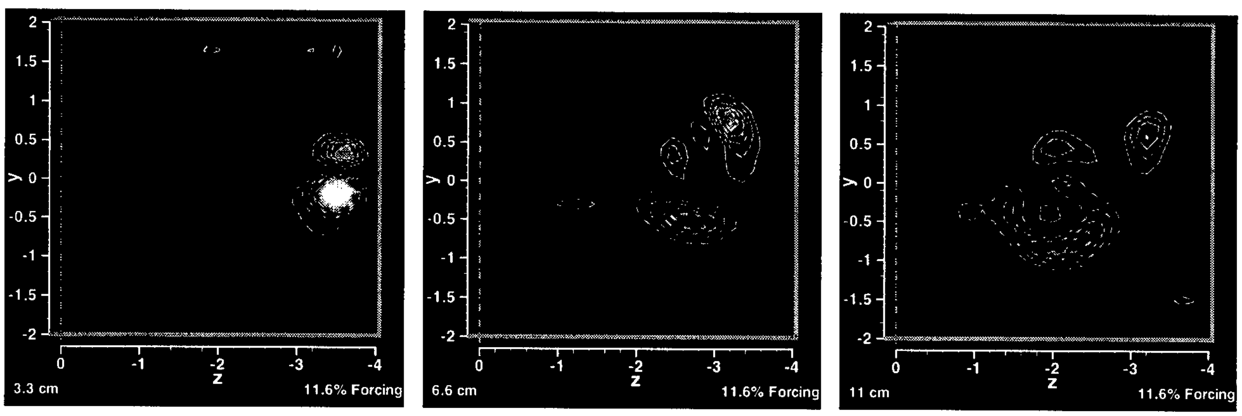


Figure 4. Downstream evolution of ω_x in the wake for one phase in the forcing cycle. Data planes are at x = 3.3, 6.6, and 11 cm. Contours are ±3, ±5, ±7, ... (s^{-1}). Dashed lines indicate negative ω_x.

4. *Combined Concentration/Velocity Measurements*

Simultaneous information on a passive scalar (e.g. concentration field ξ) and the velocity field (u, v, w) is desirable in fluid flow and mixing studies. Concentration/velocity correlations such as $\overline{u'\xi'}$ and $\overline{v'\xi'}$ appear in the Reynolds-averaged conservation equations. Information on these correlations can also be useful to LES simulations. In addition, it is noted that a fluid flow is commonly visualized using a passive scalar (e.g. a dye) and the vorticity field is directly derived from the velocity field. Simultaneous visualization of flow structure and vorticity field can be a valuable tool in discovering and understanding flow physics.

One approach for obtaining simultaneous data on velocity and concentration in a two-stream mixing geometry is to premix the alcohol/CD/lumophore phosphorescent complex in one stream, while the other stream is premixed with the alcohol/lumophore combination. The intensity field from the first image is used to infer the CD concentration in much the same way as in the laser induced fluorescence (LIF) technique. The velocity field is determined, as before, by correlating the displacement of small regions in the first image with those in the second (delayed) image. The intensity field within each tagged region is, however, no longer uniform as in the examples described so far.

Sample results from this approach are depicted in Figure 5. The flow field is that of a vortex ring discharging into an ambient and interacting with a solid wall. The flow is at a late stage of evolution, after the secondary vortex ring has already formed due to boundary layer separation and is moving away from the wall [11]. A 3-cm region of the flow next to the wall is illuminated by parallel bands of laser light. The resulting normalized concentration field ξ is shown in Figure 5(a). The range of ξ is such that $\xi = 0, 1$ correspond to pure ambient and vortex ring fluids, respectively. The corresponding velocity field is obtained using the image in Figure 5(a) and its delayed counterpart (not shown here; time delay $\Delta t = 19$ ms due to the low flow speeds) and correlating small regions within each illuminated band. The velocity field remapped onto a regular grid is shown in Figure 5(b). To facilitate the interpretation of the data, the LIF visualization in Figure 5(c) illustrates the qualitative features of the flow at this instant in time.

The approach just described suffers from the deficiency that it is not capable of providing velocity information in the portions of a flow with zero (or very small) concentration of the phosphorescent complex. To remedy this, we have devised an alternate method where the traditional LIF technique (e.g. based on using fluorescein as a tracer) is combined with MTV using a uniform concentration of our phosphorescent compound. Results show that one can design experiments with minimal cross-talk between the LIF and MTV signals. Figure 6 depicts an example of simultaneous passive scalar and vorticity fields obtained with this approach in a forced wake. Such data provide useful insight into the flow structure as interpreted based on passive scalar interfaces (i.e. a typical flow visualization) and the underlying vorticity field. It can be seen

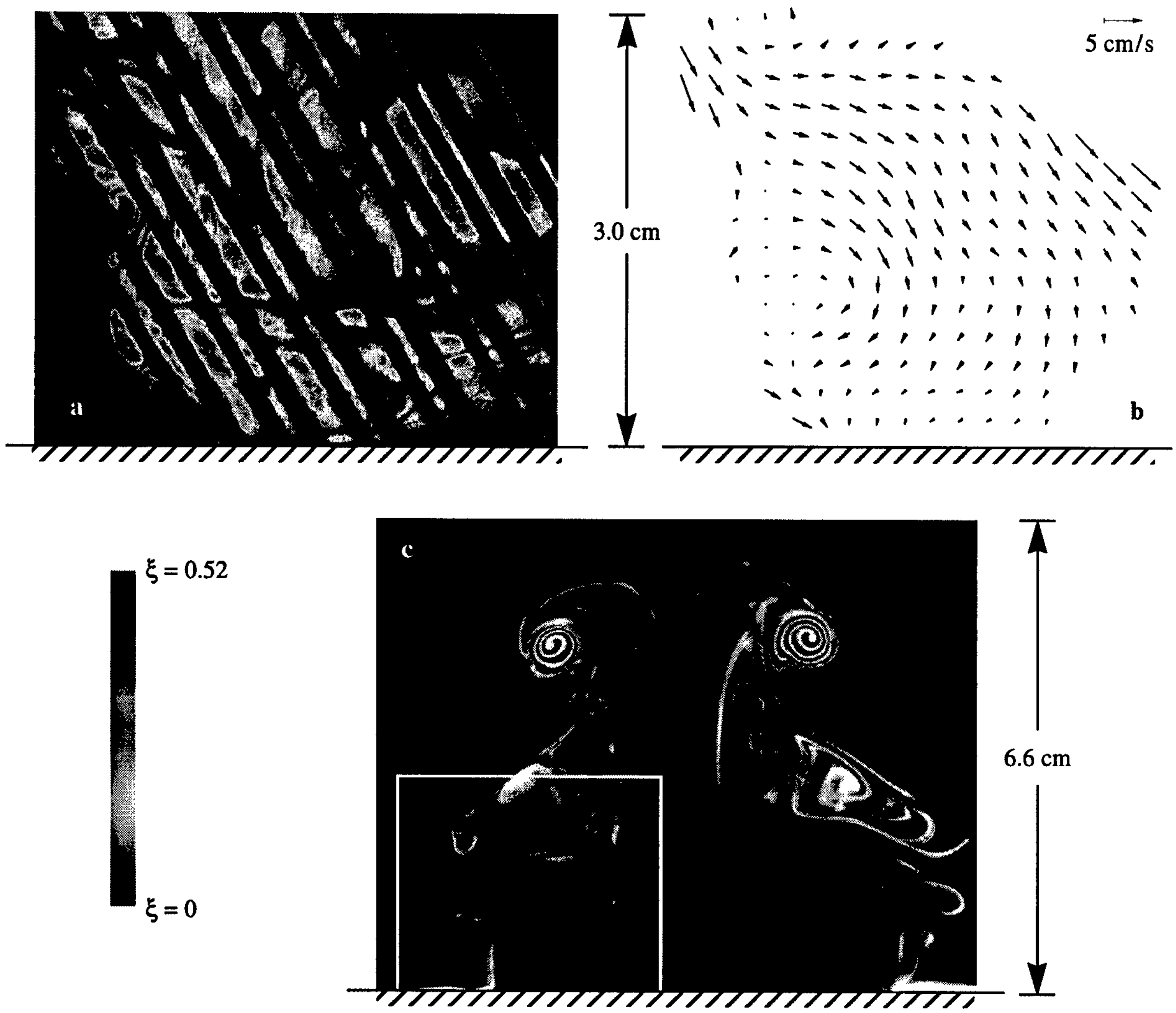


Figure 5. (a) Passive scalar concentration field derived from an image 1 μs after laser tagging; (b) velocity field determined using (a) and the corresponding delayed imaged; (c) LIF visualization of the gross features at this instant in time. The highlighted box indicates the region in (a) and (b).

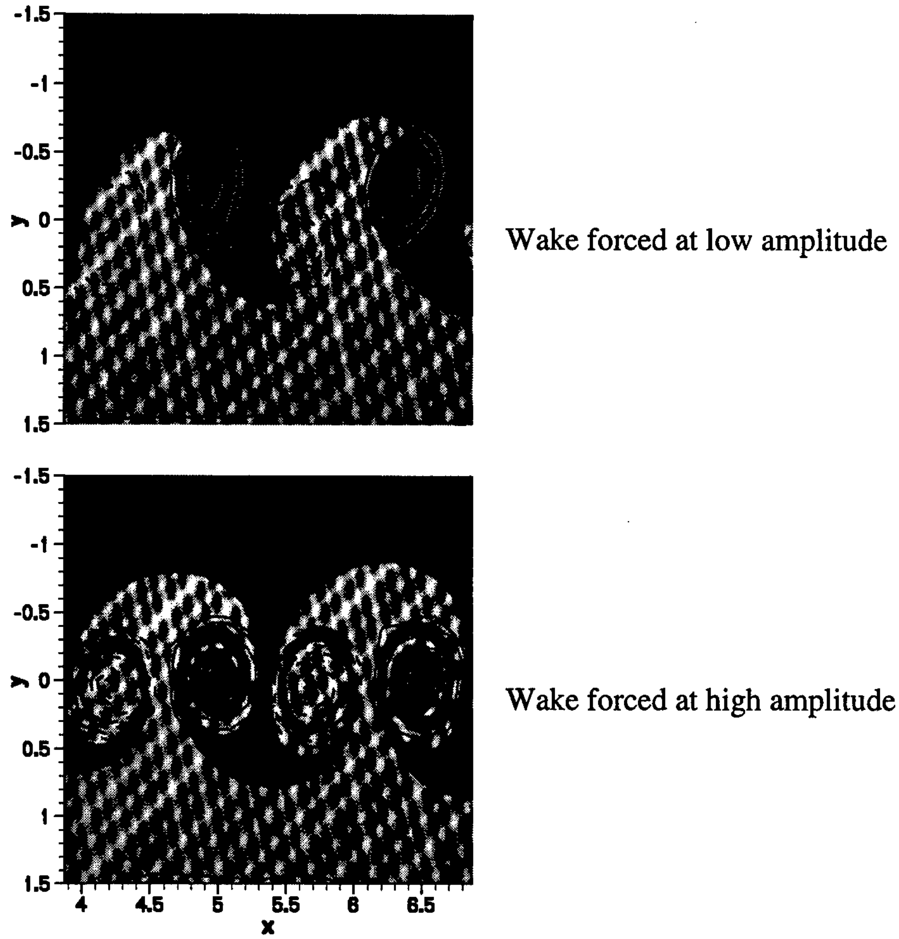


Figure 6. Simultaneous passive scalar (LIF) and vorticity (MTV) fields in a forced wake. Flow is from left to right. Vorticity contours are ±4, ±6, ±10, ±14, ±18, ±22, ... (s^{-1}).

that in the case of low amplitude forcing the vorticity has already rolled up into isolated regions, a feature not readily apparent upon examining the mixing interfaces. For high forcing amplitude, the "jelly-roll" pattern of mixing interfaces coincides with the locations of the isolated vorticity concentrations.

The technique described here has recently been used for simultaneous concentration/velocity measurements in natural and forced two-stream turbulent mixing layers [16]. Preliminary data on the mean and fluctuating components of the velocity and concentration fields agree with previous information reported in the literature. Additionally, however, our data provide new information on the correlation between concentration and velocity fluctuations and how it is influenced by external forcing. These results form part of the PhD thesis of Mr. Colin MacKinnon, due to be defended in the fourth quarter of 1998.

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